Wavelength tuning of Titanium Sapphire Laser by its own crystal birefringence

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Abstract: We report for the first time to our knowledge an experimental demonstration of wavelength tuning in a broadband-emitting Ti: sapphire laser crystal based on its own birefringence properties. To investigate the tuning characteristics of the spectral filter, we have used Jones-Vector formalism. The calculated wavelength-selective tuning matches very precisely the experimental observations.

OCIS codes: (140.3590) Lasers, Titanium; (160.1190) Anisotropic optical materials

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1. Introduction

Wide band tunable lasers with precise and reliable wavelength selection are required in many fields of science and technology. There are, however, many difficulties with such lasers related to the ability to operate the laser in narrow band maintaining a broad tuning range. Many of these devices are based on intracavity frequency tuning by use of tilted birefringent plates or diffraction gratings [1-4], but these intracavity elements increase the complexity and cost and decrease the laser efficiency. Moreover, these devices are somewhat limited by the output energy owing to optical damage. Recently the authors have reported a simple and

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powerful method for wavelength-selective tuning in broadband-emitting pulsed lasers based on the laser crystal own birefringence [5].

Nowadays among broadly tunable solid-state laser media titanium-doped sapphire is one of the most interesting due to its broad vibronic fluorescence which spans from 680 to 1100 nm. On the other hand, the major disadvantage of this type of laser to get tuning in the pulsed regime is the high-gain and relatively short fluorescence lifetime (3.2 μs) [6].

In this work we report for the first time to our knowledge an experimental demonstration of broadband wavelength tuning in a Titanium Sapphire pulsed laser based on the birefringence of the active crystal, as well as a theoretical treatment of the operation of the device.

2. Experimental setup

The laser experiments were performed with a 0.25% Ti doped, a-cut $Ti:Al_2O_3$ crystal plate furnished by Roditi I. C. L., by using a quasi-longitudinal pumping scheme, shown in Fig. 1, with a frequency-doubled Nd:YAG laser (9 ns pulse width). The pumping beam was applied slightly oblique to avoid damage to the mirrors. θ_i represents the angle of incidence and φ describes the rotation of the crystal plate around its own normal.

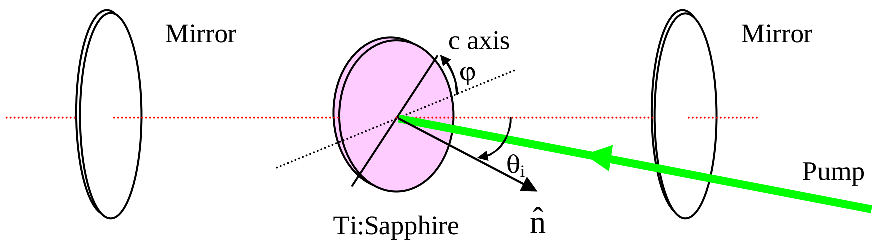

Fig. 1. Experimental set-up for the self-tuned $Al_2O_3:Ti^{3+}$ laser.

At 532 nm the value of the absorption coefficient is 3.0 cm^{-1} [7]. The pumping beam, having a diameter of 7 mm, was focused 15 cm behind the plate by using a 50 cm focal lens to avoid damaging the plate. The resonator was a 15 cm long symmetric confocal one, with two high reflectivity broadband coated mirrors (R > 95 % in the 735-875 nm band).

The frequency tuning in $Ti:Al_2O_3$ laser was obtained by locating the 500 μm thick crystal plate (c-axis in face of plate) at the center of the resonator at an angle close to the Brewster's angle ($\theta_B \approx 60^o$). The crystal was placed on a holder which allowed the rotation of the plate in its own plane (angle φ in Fig. 1). The threshold pump energy was about 50 mJ when the crystal *c*-axis formed an angle of φ=45º with the incidence plane. For a pump energy of 210 mJ, the temporal output of the $Ti:Al_2O_3$ laser consisted in a pulse 20 ns wide, with a delay of 90 ns respect to the pump pulse.

The low resolution spectral detection of the laser output pulse was performed by using a Jobin Ivon TRIAX 190 monochromator with a Hamamatsu InGaAs array giving a resolution of 0.5 nm. High resolution laser spectroscopy was achieved with the help of a 1 m monochromator and an extended infrared Hamamatsu photomultiplier system giving a resolution limit of 0.16 Å.

3. Results and discussion

3.1 Experimental tuning

The laser emission can be spectrally tuned in a range from about 750 nm to 870 nm when one varies the φ angle by rotating the sample in its own plane. The tuning curves experimentally obtained are represented in Fig. 2 for a pump energy of 210 mJ and an incidence angle

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$\theta_i = 56^o$, where two different tuning orders are shown. The shortest wavelength laser peak corresponds to an orientation of the plate in which the *c*-axis forms an angle φ of 20^o with the incidence plane (horizontal). The remaining spectra were obtained by rotating the plate in steps of 5^o. For angles φ lower than 20^o or higher than 80^o no tuning effect is observed, the obtained spectrum is much broader and its peak wavelength, (around 780 nm) does not change when the plate is rotated (as in the case of $Ti{:}Al_2O_3$ lasing without filtering). The lasing efficiency was also higher at low φ angles. This asymmetry is due to anisotropy in the pump absorption and in the stimulated emission cross-sections, the values of which are both about twice for the polarization component parallel to the c-axis than for the perpendicular one [6,8].

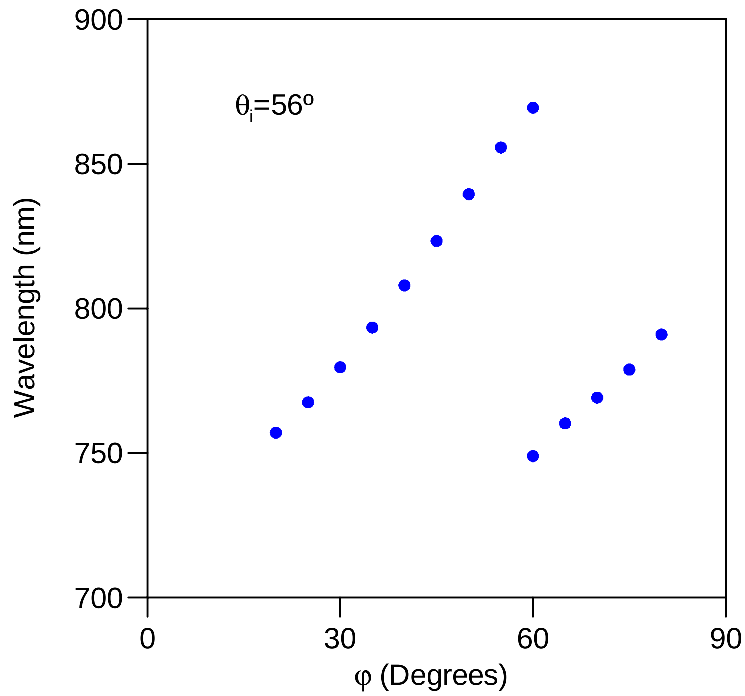

Fig. 2 Tuning range ($\theta_i = 56\,^o$) of Ti-sapphire laser as a function of φ.

3.2 Theoretical fitting of the frequency tuning

The wavelength selection occurs due to the combined effect of the plate surfaces and the crystal anisotropy. In the case of an angle of incidence close to the Brewster's angle, polarization in the plane of incidence is favoured (*p* polarization). On the other hand, the crystal anisotropy produces different retardations (δ_1 and δ_2) of the laser field components along the two principal directions, which changes the polarization of the wave inside the crystal. The relative retardation between the components $\Gamma=\delta_1-\delta_2$ depends on the plate thickness, the wavelength λ and the tuning angle φ. The maximum transmittance of the system will correspond to that wavelength for which the polarization of the wave inside the crystal does not change, that is to say, the wavelength λ_{max} for which the retardation in the plate is a multiple of 2π: $\Gamma(\lambda_{max},\varphi,..)=2m\pi$ $(m\in Z)$.

The expression for the tuning curves can be straightforwardly obtained [9-10]:

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$$\lambda_{max}(\varphi) = \frac{e}{m}\left[n_e \sqrt{1 - \sin^2\theta_i \left(\frac{\sin^2\varphi}{n_e^2} + \frac{\cos^2\varphi}{n_o^2} \right)} - n_o \sqrt{1 - \frac{\sin^2\theta_i}{n_o^2}} \right] \tag{1}$$

where e represents the plate thickness, θ_i the incidence angle, and n_o and n_e the ordinary and the extraordinary principal refractive indices respectively.

Figure 3 shows a smaller tuning range (for φ varying between 40º to 60º) obtained by rotating the crystal in steps of 0.37º for a pumping energy of 210 mJ. In this figure, the tuned laser emission wavelength for the titanium sapphire laser (dots), is compared with the calculated wavelength for maximal transmittance (from expression (1)) of the birefringent filtering (continuous green line), both of them as a function of φ.

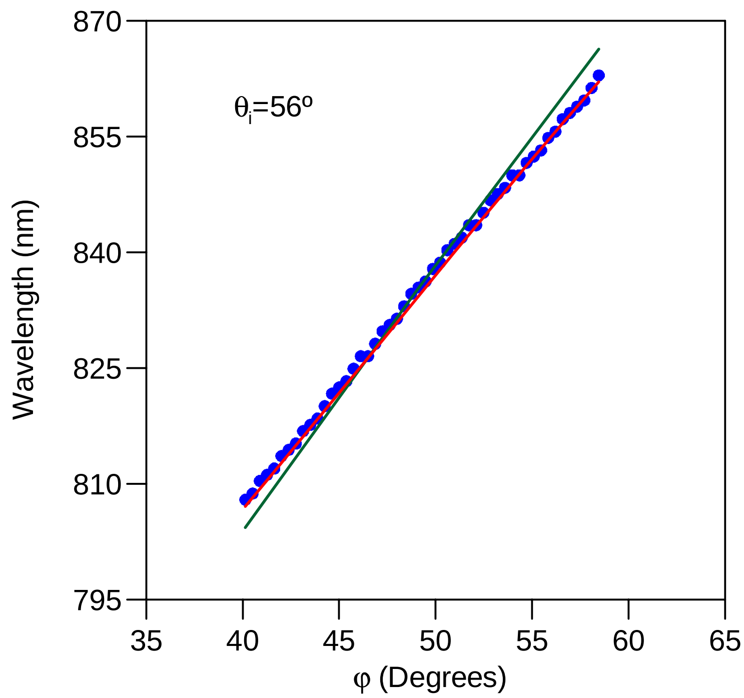

Fig. 3. Tuning range for the Ti-sapphire laser as a function of φ. The dots are the experimental points; the solid green line is the theoretical prediction from expression (1); the solid red line is the prediction after nonlinear biaxial correction.

A slight discrepancy is observed between the experimental slope and the one predicted by the expression (1), which can not be explained from the tolerances in plate thickness, c-axis or incidence angle orientations. Instead, the origin of such discrepancy can be explained by analyzing the behavior of the wavelength corresponding to the maximum of the laser emission (λ_{max}) as a function of the pump energy. In Fig. 4 one can observe that the value of λ_{max} is not constant but increases for increasing values of the pump energy. As the rest of experimental parameters are fixed (θ_i=56º, φ=45º) this result suggests a nonlinear behavior of the refractive indices of the sample. According to it, an increase of the field intensity of the cavity modes will produce a small change in the refractive indices of the sample and therefore, in its birefringence, so the condition $\Gamma(\lambda_{max})=2m\pi$ will be fulfilled for a different value of λ_{max}. In the tuning curve shown in Fig. 3 this effect must be also present, and explains why the values

#6143 - $15.00 US Received 23 December 2004; revised 11 February 2005; accepted 14 February 2005

of λ_{max} and therefore the slope of the tuning curve obtained from expression (1) are different from the experimental results.

In this sense, we have verified that introducing added controlled losses in the resonator by means of a glass plate and keeping the same pumping energy, which therefore diminishes the power density inside the crystal, the slope of the experimental tuning curve of the Fig. 3 increases, and gets closer to the one predicted by expression (1).

In consequence we proceed to analyze whether a small modification of the refractive indices can explain the experimental tuning curves more accurately. As the pump and emission beams are *p* polarized and the tuning angle $\varphi \neq \{0º,90º\}$, the originally degenerated refractive indices $n_x=n_y=n_o$ are expected to become different $\delta n=n_x-n_y\neq 0$ under the action of a strong electric field and the crystal thus changes from uniaxial to biaxial. For simplicity, we will assume that only the values of n_x and n_y change under the action of the electric field: the direction of the z axis remains being parallel to the plate surfaces and n_z does not change. Every incident wave on the plate splits inside the crystal into two waves propagating with different velocities. The refractive indices (n_1,n_2) corresponding to those waves can be determined by solving the Fresnel's equation [11], and the tuning curve in terms of the refractive indices (n_1,n_2) will be finally given by:

$$\lambda_{max}(\varphi) = \frac{e}{m}\left[\sqrt{n_2^2-\sin^2\theta_i} - \sqrt{n_1^2-\sin^2\theta_i}\right] \qquad (2)$$

In the case of an uniaxial crystal: $n_x=n_y=n_o$, Eq. (2) reduces to (1).

We have fitted the theoretical tuning curve given by Eq. (2) to the experimental tuning curve shown in Fig. 3. A good fitting is possible with realistic values of changes in the refraction indices ($\Delta n \cong 10^{-4}$) similar to the expected changes in the refractive indices of this material due to a nonlinear effect (continuous red line in Fig. 3).

The linear dependence of λ_{max} with the pump energy was fitted by using the biaxial model with a nonlinear dependence of the refractive indices respect to the field intensity of the cavity modes (considered approximately proportional to the pump energy). A good fitting is obtained for not very high pump energies as can be seen in Fig. 4. Besides, the changes of the refractive indices obtained from this fitting corresponding to a pump energy of 210 mJ are in good agreement with the values obtained from the previous fitting of the tuning slope of Fig. 3.

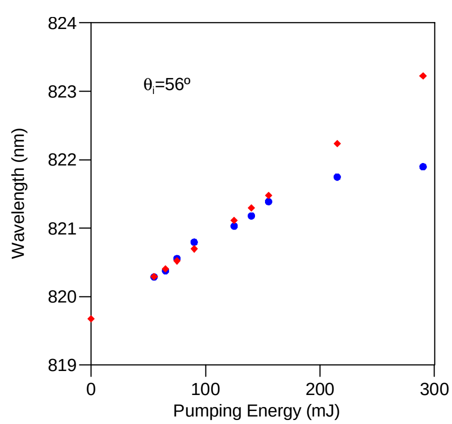

Fig. 4. Wavelength corresponding to the maximum of the laser emission (λ_{max}) for different pump energies (blue dots) and the theoretical values obtained from the fitting to a model with nonlinear dependence of the refractive indices (red rhombs).

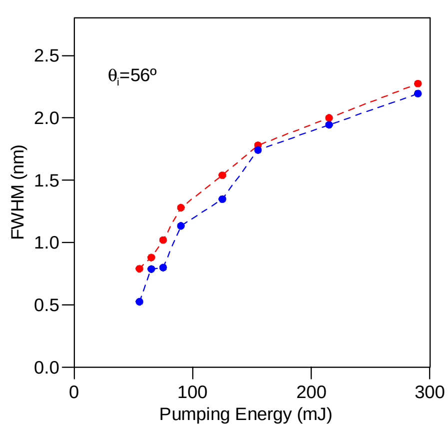

Fig. 5. Experimental full width at half maximum (FWHM) of the laser output for different pump energies (blue dots) and calculated values (red dots)

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The saturation effect for the highest pump energies observed in Fig. 4 is surely due to a bleaching effect of the fundamental state, because a fall of about 20% in the absorption coefficient is expected in these conditions.

Another fundamental question to be addressed in the tuning process is the spectral width of the laser output pulse. In Fig. 5 the dependence of the FWHM of the laser output with the pump energy is shown. In order to analyze the width of the laser output a Jones-vector formalism was used [5]. We have calculated the eigenvalues of the Jones matrix that describes the system (passive birefringent Brewster plate with its optic axis parallel to the plate surface) and gives its transmittance, defined as the flux remaining in the resonator after n-round trips through the crystal plate. As Fig. 5 shows, the experimental results and the theoretical predictions are in good concordance. For increasing values of the pump energy the average lifetime of the laser modes inside the cavity decreases so that the filtering is less efficient and the FWHM of the laser output increases from 0.5 nm up to 2 nm for maximal pumping energy. If we compare our results with the ones obtained in other broad band vibronic lasers, by using Lyot-type filters, it would be worthy to notice that the linewidth produced by a four-plate quartz filter in a high-gain pulsed dye laser was measured to be 0.2 nm [4].

Finally, as we mentioned above, the crystal anisotropy influences the pump absorption and gain in the laser medium and, as a consequence, changes by a factor of three in the laser threshold along the tuning range may occur. As regards to the theoretical filter bandwidth, if the crystal anisotropy is taken into account and the same experimental conditions are supposed, an additional increase of about ten percent is obtained.

4. Conclusion

As a conclusion, we have demonstrated frequency tuning in a Ti: sapphire pulsed laser by using a thin birefringent active crystal plate. From a practical point of view this approach is important because the absence of intracavity elements increases the laser efficiency and reduces its complexity and cost. On the other hand, this compact setup could be easily used for injection locking in more complex Ti:sapphire lasers.

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